Forecasting Future Sea Ice Conditions: A Lagrangian Approach

{Bruno Tremblay}
Lamont-Doherty Earth Observatory of Columbia University
phone: (514) 398-4369 fax: (514) 398-6115 email: bruno.tremblay@columbia.edu

Award Number: N000141110977
http://brunotremblayseaice.jimdo.com
http://extranet.nsidc.org/IceMotion/

LONG-TERM GOALS

1- Show from observations whether the dynamics of the multi-year pack ice has a influence on the location of the following summer MIZ.

2- Determine the source regions of summer sea ice in coastal zones using a back trajectory model forced with satellite-derived sea-ice drift (Maslanik et al. 1995, Emery et al. 1997, Meier et al. 2000, Tschudi et al. 2010)

3- Assess whether the source region of sea ice melting in peripheral seas in the GCMs participating in IPCC AR5 agree with observed source region patterns from the satellite-derived dataset.

4- Compare Lagrangian ice trajectories in the model with satellite datasets.

5- Repeat this comparative analysis for three critical climate horizons: a base period with a dominant perennial sea ice cover and two projection periods in the 21st Century (2040-2060 and 2080-2080).

OBJECTIVES

1- Reduce uncertainties in future sea ice extent prediction from climate models participating in CMIP5. These include temporal evolution and geographical distribution of sea ice cover and transport pathways.

2- Improve our understanding of the strengths and/or limitations of GCM predictions of future ice edge positions.

3- Identify limitations in the ability of GCMs to simulate source regions for sea ice being advected into marginal ice zones (MIZs) and thus provide guidance for developing more reliable forecasts of the future evolution of transports of material between remote areas of the Arctic.

4- Quantify GCM biases in the balance of thermodynamically formed, in situ, ice production as opposed to advection gain and loss.

5- Develop a seasonal forecast model for sea ice extent using satellite-derived ice concentrations, PIOMAS ice thickness, RGPS ice deformation, Reanalysis atmospheric data and Lagrangian sea-ice back trajectories to estimate thermodynamic and dynamic (advection) ice loss.

APPROACH

We use a Lagrangian trajectory model to track the dynamics of the multi-year and first year ice boundary, defined as the minimum ice edge in September. To this end, we 1) identify the source regions for sea ice that melts and sea ice that survives the summer melt season in each of the Arctic peripheral seas as well as 2) sea ice area export through Fram Strait, and net sea-ice divergence/convergence in each of the Arctic peripheral seas for each year of satellite observations or modeled ice motion. The first diagnostic tells us something about the processes responsible for promotion of first to multi-year ice. The second diagnostic can be used for seasonal forecasting of the minimum sea ice extent. The Lagrangian Model is forced with weekly mean satellite-derived sea-ice drifts, and monthly mean sea-ice drift from the Coupled Model Intercomparison Project 5 (CMIP5) GCMs. The satellite-derived ice-motion vectors come from the NSIDC's Polar Pathfinder (PP) product, which is generated using brightness temperatures from passive microwave radiometers (SSM/I, SSMIS, SSMR, AVHRR, AMSRE) combining the bootstrap and NASA-Team algorithms (Fowler et al, 2013). The PP data product also assimilates buoy data, which influences the product's ice drift at grid-points within a radius of a few hundred kilometers of the buoy track. In the summer, when the cross-correlation algorithm between brightness temperature images has difficulties identifying features on the ice surface, the data set relies on both buoy data and free-drift estimates, the latter are derived from reanalysis of sea level pressure data.

WORK COMPLETED

The Lagrangian trajectory model forced with satellite-derived or GCMs sea-ice drift data was updated. The model was used by three students: Patricia de Repentigny (Masters thesis submitted for publication to Journal of Climate (JClim)), James Williams (PhD student, paper accepted with revisions to Journal of Climate) and Charles Brunette (Bachelor of Physics, paper in preparation) working on long-term and seasonal (pan-Arctic and regional) forecasting of Arctic sea ice respectively. See below for results from this research.

The PanArctic seasonal forecasting model of the minimum sea ice extent is completed (Williams et al, Journal of Climate, in revision).

The decadal forecasting of the minimum sea ice extent based on the output of 30 ensemble members of the Community Climate System Model Verson 1, is completed (DeRepentigny et al, Journal of Climate, in revision).

The work for the regional seasonal forecasting model of the minimum sea ice extent is completed (Tremblay et al, in prep).

Charles Brunette is now a Masters students at McGill working with Tremblay. Starting in May 2016, he will work on a Lagrangian energy budget of Arctic sea ice based entirely on observations in order to determine the keywhich factors most important in explaining the promotion of first year ice into multi-year ice, including ocean heat fluxes, radiative and turbulent fluxes.

The analysis of the Transnational sea-ice transport in a warmer, more mobile Arctic is completed. The PIs and Patricia DeRepentigny will meet in New York City in November, 2015, to finalize a paper on this topic. The results will be presented at the AGU in December.

We have added features to the Ice Tracker program originally developed by Chuck Fowler at the University of Colorado (not publicly available). The new Ice Tracker is hosted on the http://thepolarhub.org/ web site based at Columbia University that was developed under a separate education initiative funded by the National Science Foundation (PI: Pfirman). The Ice Tracker is an online program that allows users to plot the trajectory of a sea ice floe (backward or forward in time) starting from any ice covered area in the Arctic Ocean within the satellite era of 1979-2013. The new Ice Tracker allows the user to select multiple trajectories, and to overlay other fields (air temperature, ice age, ice thickness, etc) on the Lagragian trajectories. The data can also be saved for off-line analysis. This tool is being used in classroom teaching by Pfirman and Tremblay, in informal educational applications through the PoLAR site. It has been used by Smethie, Schlosser and Newton (one of our co-PIs) for research into freshwater component transport, and will be useful for a variety of additional applications including sediment, nutrient and pollutant transport by sea ice, seasonal forecasts, rescue, emergency response, educational purposes, etc. The site is also available on the National Snow and Ice Data Center http://extranet.nsidc.org/IceMotion/.

In the past year, the Lagrangian-tracked ice age data set was published by NSIDC (Tschudi et al., 2015). Previously, it was a research level dataset with ad hoc updates and support. While it should probably still be considered research level, the product now has full documentation, user support through NSIDC, with better documented and reproducible software, and, importantly for this project, the source data now has a citable home.

During the past year, research conducted under this project encountered errors and limitations in the underlying ice motion fields at NSIDC. These include: potential biases in the passive microwave motions, errors in some buoy velocities, errors in some AVHRR daily fields (mostly in the Southern Hemisphere), and limitations in the optimal interpolation method used. Improving the underlying data set is beyond the scope of this project. However, we evaluated the motions and provided that input to NSIDC to help assess the issues and their impact on this project and other uses of the dataset. While the errors are not negligible, the performance was on par with similar products in a recently published evaluation (Sumata et al., 2015) and the products can still provide reasonable motion estimates at weekly scales and thus provide useful input to this project, especially since 2000?. However, to take full advantage of the ice motion data, improvements are needed. Thus we worked with NSIDC on evaluating the errors and investigating steps to ameliorate the errors, both short-term (minor changes) and long-term (major version change). These consultations were incorporated into a revised version to be released soon (November 2015) by NSIDC that fixeses the most easily addressed issues. A proposal has been submitted to NASA to fully reprocess the motion and age products and rectify the more major issues.

RESULTS

Williams, J., L.B. Tremblay, R. Newton, R. Allard, "Dynamic preconditioning of the September sea-ice extent minimum", Journal of Climate, Accepted for publication with revisions.
This paper is a direct contribution to Objective #5.
Abstract: There has been an increased interest in seasonal forecasting of the sea ice extent in recent years, and in particular the minimum SIE. We present a dynamical mechanism, based on winter

preconditioning through first year ice formation, that explains a significant fraction of the variance in the anomaly of the September sea ice extent from the longterm linear trend. To this end, we use a Lagrangian trajectory model to backtrack the September sea-ice edge to any time during the previous winter and quantify the amount of sea-ice divergence along the Eurasian and Alaskan coastlines. We find that coastal divergence that occurs later in the winter (March, April and May) is highly correlated with the following September sea-ice extent minimum ($r = -0.73$). This is because the newly formed first year ice does not have time to grow to the necessary thickness required to survive the following summer melt. We then connect the mean winter large-scale circulation pattern- characterized by the mean DJFMA Arctic Oscillation index- to the anomaly of sea-ice divergence (a proxy for first year ice area) along the Eurasian coast ($r = 0.71$). Indeed, it follows that the mean DJFMA Arctic Oscillation is significantly correlated with the following September sea-ice extent anomaly from the longterm linear trend. Finally, we note a positive trend in the amount of sea-ice divergence along the Eurasian coastline during winter, highlighting the increasing importance of wintertime dynamics on the September sea-ice extent minimum suggesting development of a real-time, operational sea-ice velocity product in order to develop an observation based forecasting method using the physical mechanism presented here.

DeRepentigny, P., L.B. Tremblay, R. Newton, S. Pfirman, "Patterns of Sea-Ice Retreat in the Transition to a Seasonally Ice-Free Arctic, Journal of Climate, in revision.
This paper is a direct contribution to Objective #1-2.
Abstract: We investigate the patterns of sea-ice retreat in the Arctic Ocean using two Global Climate Models (GCMs) that have profound differences in their large-scale mean winter atmospheric circulation and sea-ice drift patterns. The Community Earth System Model Version 1 (CESM-LE) has a mean sea-level pressure pattern that is in general agreement with observations for the late 20th century. The Community Climate System Model Version 4 (CCSM4) exhibits a bias low in its mean sea-level pressure with a deeper Icelandic Low. We present a dynamical mechanism through which the large-scale mean winter atmospheric circulation has significant effect on the following September sea-ice extent anomaly by influencing ice divergence in coastal seas. We use a Lagrangian model to backtrack the 80 degree N line from the time of the melt onset to its prior position throughout the previous winter and quantify the area of divergence from the Pacific (Beaufort and Chukchi seas) and the Eurasian (East Siberian, Laptev and Kara seas) sectors. We find that CCSM4 simulates larger areas of sea-ice divergence in the Beaufort and Chukchi seas and smaller areas of divergence in the Eurasian sector when compared to CESM-LE, leading to a Pacific-centric sea-ice retreat. On the other hand, CESM-LE shows a more symmetrical retreat between the Pacific, Eurasian and Atlantic sectors of the Arctic. Given that a positive trend in the AO index is a robust feature of GCMs participating in the fifth Coupled Model Intercomparison Project (CMIP5), our results suggest that during the ongoing transition to a seasonally ice-free Arctic, the sea-ice retreat will continue to be Pacific-centric.

Tremblay, L.B., C. Brunette, J. Williams, R. Newton, S. Pfirman, "Regional forecast of the minimum sea ice extent: a Lagrangian approach, now an AGU abstract, to be submitted in Journal of Physical Oceanography.
This work is a direct contribution to Objective #5.
Abstract: In this contribution we extend the pan-Arctic analysis presented in Williams et al. (2015) to produce a regional forecast of sea-ice conditions for each of the Arctic peripheral seas including the Beaufort, Chukchi, East Siberian, Laptev and Kara seas. The model builds on the finding that the mean large scale sea ice circulation the previous winter determines where the following summer minimum sea ice extent will be?. We show that, in particular, the mid to late winter coastal sea-ice divergence

plays a major role. When ice divergence occurs late in the winter, new ice forms but it does not have the time to grow to sufficient thickness to survive the following summer melt. To produce a regional forecast, we use a Lagrangian sea-ice model to backtrack an imaginary line defining the boundary of a given sea, starting from the beginning of the melt season in June and ending in November of the previous year. Results show that the position of the ice edge in each of the peripheral seas of the Arctic is well correlated with the previous winter's divergence. The maximum correlation is obtained when the synthetic ice edge is backtracked from May to February. Note that, unlike the previous pan-Arctic study of Williams and colleagues in which the net ice divergence could be correlated with the winter mean Arctic Oscillation index, this regional analysis requires sea ice drifts in order to calculate the winter mean ice divergence along the coast. This finding supports the need for continuous production of real-time satellite-derived sea-ice velocity vectors, which can now be used for observation-based regional forecasting.

Newton, R. S. Pfirman, B. Tremblay, P. Derepentigny, "Transnational sea ice transport in a warmer, more mobile Arctic, now an AGU abstract (2015), to be submitted for publication in December 2015.
This work is a direct contribution to Objective #3.
As the Arctic sea ice thins, summer ice continues to shrink in its area, and multi-year ice becomes rarer, winter ice is not disappearing from the Arctic Basin. Rather, it is ever more dominated by first year ice. And each summer, as the total coverage withdraws, the first year ice is able travel faster and farther, carrying any ice-rafted material with it. Micro-organisms, sediments, pollutants and river runoff all move across the Arctic each summer and are deposited hundreds of kilometers from their origins. Analyzing Arctic sea ice drift patterns in the context of the exclusive economic zones (EEZs) of the Arctic nations raises concerns about the changing fate of "alien" ice which forms within one country's EEZ, then drifts and melts in another country's EEZ.

We have developed a new data set from satellite-based ice-drift data that allows us to track groups of ice "pixels" forward from their origin to their destination, or backwards from their melting location to their point of formation. The software has been integrated with model output to extend the tracking of sea ice to include climate projections. Regions of potential conflict are identified, including several national borders with extensive and/or changing transboundary sea ice transport. For example, results indicate that Russian sea ice dominates the EEZ of Norway, as expected, but with increasing ice mobility it is also is exported into the EEZs of other countries, including Canada and the United States. These data are a starting point for discussion of transborder questions raised by "alien" ice and the material it may import from one nation's EEZ to another's.

The following works are contributions to Objective #1-2-4. These works improves our understanding of the role of ocean heat fluxes on future sea-ice retreat. It is not a direct contribution because it does not rely on a Lagrangian approach to study the question.

Slavin, A., L.B. Tremblay, D. Straub, "Vertical ocean heat fluxes beneath Linear Kinematic Features in the Arctic Ocean, to be submitted to the Journal of Geophysical Research, Ocean this month.
Abstract. Measured ocean heat fluxes in the central Arctic are typically small in winter - of the order of 1 W/m^2 or smaller. In fact the Cold Halocline Layer (CHL) - a layer of cold but saltier waters beneath the mixed layer and above the Atlantic waters - provide a strong barrier to vertical exchange in the surface ocean. In this paper, we show modeling evidence, supported by observations, for strong Ekman pumping velocities beneath active leads (Linear Kinematic Features, LFKs) where discontinuity in the sea-ice drifts and the surface ice-ocean stresses momentum transfer are present. To this end, we use a

high resolution (3.75 – 5.5 km) coupled ice-ocean model with a good representation of the CHL and Near Surface Temperature Maximum (NTSM) – the MITgcm – forced with contemporaneous atmospheric forc- ing from the Japanese Reanalysis Project (JRA-25). Simulated vertical velocities near LKFs can extend hundreds of meters below the surface, into the Warm Atlantic Layer. Typical vertical displacements in an LKF event, however, are only a few tens of meters. As such, we argue that anomalous heat fluxes under LKFs bring up heat from the shallower NSTM, and possibly the Summer Pacific Waters. To assess the overall impact of LKF-related heat fluxes on the sea ice mass balance, we apply a simple linear relationship be- tween the observed ocean heat flux beneath an active LKF (McPhee et al., 2005), sea-ice velocity curl from the Radarsat Geophysical Processor System (RGPS) and Polar Pathfinder sea ice velocities. We focus on the Beaufort Sea, a region of intense active LKFs. Averaged over the Beaufort Sea, results suggest that wintertime heat fluxes associated with Ekman pumping beneath active LKFs are sufficient to melt about 11 cm of sea ice (1 $W/m^{2)}$. We suggest that this process can be important in controlling the Arctic sea-ice mass balance and a potentially important player in the recent sea-ice decline in the Beaufort Sea one that is not represented in lower-resolution global climate models. Additionally, projections of a thinning and more mobile pack ice suggest that LKF-related heat fluxes will amplify under near-future climate scenarios.

Renaud-Desjardins, L., L.B. Tremblay, "Abrupt reduction in summer Arctic sea ice and the partitioning of ocean heat flux between the Fram Strait and Barents Sea gate", now an abstract at the Ocean Science Meeting (2016), in preparation: to be submitted to the Journal of Geophysical Research in January 2016.

Abstract: We analyze two versions of the CSSM (CSSM3-4) with widely different temporal evolution of the minimum sea ice extent in the Arctic Ocean. In CCSM3, abrupt reductions in summer Arctic sea ice are present in all ensemble members leading to a seasonally ice-free Arctic as early as 2040 (Holland et al, 2006). In all ensemble members, the abrupt sea ice declines are preceded by a pulse of heat of Atlantic origin into the Arctic Ocean, causing an increase in open water area, and absorbed solar radiation at the surface triggering the positive ice-albedo feedback. In CCSM4, no abrupt reductions in summer Arctic sea ice are simulated; instead, the model simulates a slow decline in sea ice leading a seasonally ice-free Arctic by the end of the century. A key difference between the two versions of the CCSM is the partitioning of ocean heat of Atlantic origin between Fram Strait and the Barents Sea gate. In CCSM4, ocean heat fluxes increases slowly but steadily in all gates of the Arctic. When North Atlantic Drift waters enter the Arctic through the Fram Strait, they sink at depth and interact little with the sea ice cover while circulating within the Arctic Ocean. In CCSM3, the ocean heat flux through Fram Strait decreases slightly with time in the 21st century and the pulses of ocean heat enter the Arctic entirely through the Barents Sea gate. This ocean heat interacts with the sea ice cover on the northern end of the Barents Sea before merging with the Fram Strait branch at depth and leads to a negative ice thickness anomaly that is advected in part in the Fram Strait and in part in the Beaufort Gyre. The thinner (weaker) central Arctic pack ice in turns allows for more sea ice divergence along the Eurasian coastline and for a rapid transition to a seasonally ice free Arctic. The creation of new open water also triggers the ice-albedo and cloud-ice albedo feedback, with an increase in liquid water cloud and associated increase in downwelling longwave radiation.

This paper is a contribution to Objective 1-2-4. This work improves our understanding of the seasonality of an ice-free Arctic. It is not a direct contribution in that it does not rely on our Lagrangian model.

Tremblay, B., R. Cullather, P. DeRepentigny, S. Pfirman, R. Newton, "Seasonal sea ice extent: How free is free? Now a Fall AGU abstract (2015), in preparation: to be submitted for publication in the Spring of 2016.

Abstract: The idea of a seasonally ice-free Arctic within the next few decades is more and more a reality. In this contribution we document the seasonality of the sea ice retreat and in particular we pose the following question: for how long will the Arctic Ocean be ice free on average each year? To this end, we analyze the seasonal cycle in the sea-ice extent simulated by the Community Earth System Model 1 - Large Ensemble (CESM1-LE) in the 21st century. CESM1-LE simulates a realistic late 20th, early 21st century Arctic climate with a seasonal cycle in sea ice extent and rate of decline in good agreement with observations. Results from this model show that the length of the ice-free season is relatively short even by the end of the 21st century, with ice-free conditions mainly present in August to October. This results in a much larger amplitude seasonal cycle when compared with the late 20th century climate. We also discuss the impact of such changes in the seasonality of the sea ice cover on species that are dependent on sea ice for their livelihood.

Error Analysis of the Lagrangian Model:
In preparation for the Lagrangian back-trajectory work using GCMs, we have run back and forward trajectories forced with weekly and monthly sea ice drift data using code developed in the course of this proposal and compared with 12-hourly buoy data from the International Arctic Buoy Program. The results show that the use of weekly and monthly average sea-ice drift data to calculate the back-trajectories lead to a relatively small error – of the order of 50 km and 150 km for the weekly and monthly sea-ice drift forcing field, respectively. The errors are such that a Lagrangian analysis forced with GCM model output – typically at saved at monthly temporal resolution – is meaningful.

IMPACTS AND APPLICATIONS

We have developed a panArcticused our Lagrangian model to develop a seasonal forecasting model of the minimum sea ice extent (SIE) both? based on a Lagrangian model and based entirely on observations of sea ice drift and extent. This work extends by two months the lead time of the seasonal forecasts of the minimum SIE by Scroeder et al (Nature, 2014) with no loss in predictive skills. The skill of this model relies on pre-conditioning of the pack ice the previous winter via coastal divergence of sea ice.

We have applied the same approach to develop a regional seasonal forecasting model of the minimum SIE. This work clearly shows that that sea ice retreat in the Atlantic (Kara and Barents) and Pacific sectors (Beaufort and Chukchi) sectors of the Arctic are affected by ocean heat fluxes while coastal sea ice divergence is the key mechanism determining sea ice retreat in the Eurasian (East Siberian and Laptev) sector.dominant.

We applied our method to output from the 30-ensemble members of the CESM-LE1 and the CCSM4, —two models htat have widely different winter sea ice circulations—and found that a Pacific-centric retreat of sea ice may be predominate in the future ifis highly probably as long as the projection of more positive AO index in the future is correct. A positive trend in the AO is a common feature of CMIP models, and is the sort of large-scale integrative characteristic that is more reliable than regional details in model ensembles.

The IceTracker is now publicly available at http://thepolarhub.org/ and http://extranet.nsidc.org/IceMotion/. It can be used for education, environmental, and scientific

purposes. See Work Completed section for details. Impact: see
http://blogs.ei.columbia.edu/2013/12/10/explore-the-arctic-ocean-with-icetracker/

RELATED PROJECTS

Tremblay LB, Schmidt GA, Pfirman S, Newton R, DeRepentigny P., ``Is ice-rafted sediment in a North Pole marine record evidence for perennial sea-ice cover?'' Phil. Trans. R. Soc. A 373: 20140168. http://dx.doi.org/10.1098/rsta.2014.0168, 2015.

This work is not funded by ONR. It is a related activity that reconciles the ACEX ocea core and other marine record as to the onset of perrenial sea ice in the Arctic Ocean.

Abstract: Ice-rafted sediments of Eurasian and North American origin are found consistently in the upper part (13 Ma BP to present) of the Arctic Coring Expedition (ACEX) ocean core from the Lomonosov Ridge, near the North Pole (≈ 88° N). Based on modern sea-ice drift trajectories and speeds, this has been taken as evidence of the presence of a perennial sea-ice cover in the Arctic Ocean from the middle Miocene onwards (Krylov et al. 2008 Paleoceanography **23**, PA1S06. (doi:10.1029/2007PA001497); Darby 2008 Paleoceanography **23**, PA1S07. (doi:10.1029/2007PA 001479)). However, other high latitude land and marine records indicate a long-term trend towards cooling broken by periods of extensive warming suggestive of a seasonally ice-free Arctic between the Miocene and the present (Polyak et al. 2010 Quaternary Science Reviews **29**, 1757–1778. (doi:10.1016/j.quascirev.2010.02.010)). We use a coupled sea-ice slab-ocean model including sediment transport tracers to map the spatial distribution of ice- rafted deposits in the Arctic Ocean. We use 6 hourly wind forcing and surface heat fluxes for two different climates: one with a perennial sea-ice cover similar to that of the present day and one with seasonally ice-free conditions, similar to that simulated in future projections. Model results confirm that in the present-day climate, sea ice takes more than 1 year to transport sediment from all its peripheral seas to the North Pole. However, in a warmer climate, sea-ice speeds are significantly faster (for the same wind forcing) and can deposit sediments of Laptev, East Siberian and perhaps also Beaufort Sea origin at the North Pole. This is primarily because of the fact that sea-ice interactions are much weaker with a thinner ice cover and there is less resistance to drift. We conclude that the presence of ice-rafted sediment of Eurasian and North American origin at the North Pole does not imply a perennial sea-ice cover in the Arctic Ocean, reconciling the ACEX ocean core data with other land and marine records.

Robert Newton, R., S. Pfirman, P. Schlosser, L.B Tremblay, M. Murray, M. Gerrard, "White Arctic vs. Blue Arctic: A Case Study of Diverging Stakeholder Responses to Environmental Change. To be submitted to XXX in October 2015.

This work is not funded by ONR but is a related activity of the PIs that discusses what would need to be done to preserve or restore sea ice in the Arctic in the context of (potentially divergent) stakeholder interests and opinions.

***Abstract*:** The challenge of controlling, managing, or possibly reversing the impacts of human activities on our planet has an increasingly visible other dimension that has been given little attention, i.e., interests of a stakeholder community whose interest lies with "business as usual" or that hopes to benefit from environmental change. These issues are playing out now in the Arctic, as it shifts from white, ice-bound, to a seasonally ice free, blue, and resource-accessible state. There are many environmental, socioeconomic and sociocultural arguments for restoring and sustaining a year-round, ice-covered white Arctic. At the same time, there are growing interests in the opening up of a blue Arctic Ocean. The present trend of emissions of greenhouse gases to the atmosphere suggests that most

of the summer sea ice cover is likely to be lost before interventions can be implemented that would restore and sustain summer Arctic sea ice. Given this trajectory, we have to ask if we should try to restore the sea ice, in order to, for example, restore the Arctic's albedo. We will probably experience at least one, and perhaps several human generations before summer sea ice could begin to return. How will future generations feel about bringing sea ice back into regions where they have not experienced it before? What if there is international and local interest in taking action to restore sea ice, while there is domestic/federal interest in the economic advancement that open access might bring? In what forum can such questions be raised and negotiated? Answering these new questions needs new approaches – environmental change in the Arctic is proceeding quickly and without respect for traditionally cumbersome ways of processing information and moving to action. As stewards of the Arctic, the Arctic rim nations have a responsibility to establish a forum where experts can meet with decision-makers. This process should cast a wide net, including community leaders and private sector interests both in the Arctic countries and internationally. Academia, the primary knowledge generator of society, has an important role to play in such deliberations. While these issues are currently playing out in the Arctic, similar tensions are already emerging in other regions. We have an ethical obligation to examine our challenges, opportunities, and responsibilities. We need not to drift forward, but to consciously consider and decide among options.

*Bouchat, A., L.B. Tremblay, Discriminating between different sea-ice rheological models using observed deformation fields from RGPS, now an Ocean Science Meeting abstract, to be submitted for publication in the Spring 2016***.**

High resolution sea-ice dynamic models offer the potential to discriminate between sea-ice rheologies based on their ability to reproduce the satellite-derived deformation fields. Recent studies have shown that sea-ice viscous-plastic (VP) models do not reproduce the observed statistical properties of the strain rate distributions of the RADARSAT Geophysical Processor System (RGPS) deformation fields [1][2]. We use the elliptical VP rheology and we compute the probability density functions (PDFs) for simulated strain rate invariants (divergence and maximum shear stress) and compare against the deformations obtained with the 3-day gridded products from RGPS. We find that the large shear deformations are well reproduced by the elliptical VP model and the deformations do not follow a Gaussian distribution as reported in Girard et al. [1][2]. On the other hand, we do find an overestimation of the shear in the range of mid-magnitude deformations in all of our VP simulations tested with different spatial resolutions and numerical parameters. Runs with no internal stress (free-drift) or with constant viscosity coefficients (Newtonian fluid) also show this overestimation. We trace back this discrepancy to the elliptical yield curve aspect ratio ($e = 2$) having too little shear strength, hence not resisting enough the inherent shear in the wind forcing associated with synoptic weather systems. Experiments where we simply increase the shear resistance of the ice by modifying the ellipse ratio confirm the need for a rheology with an increased shear strength.

Plante, M. L.B. Tremblay, "Large scale mechanical properties derived from MODIS observations of land-fast ice and a linear elastic solid model", now an abstract at the FAMOS workshop, to be submitted for publication in the spring of 2016.

Abstract: A linear elastic solid sea-uice model is developed to simulate the internal stresses induced by wind on land-fast ice. The sea ice is assumed to behave as a 2D elastic plate. To estimate the large scale material properties of the ice, observed break up events are used together with surface stresses from reanalysis data and the sea ice model, to infer the tensile and shear strength of the ice. Brightness temperature imagery from MODIS (Moderate Resolution Imaging Spectroradiometer) on the Terra and Aqua satellites show multiple break up events of ice bridges in the southeastern Laptev Sea with a characteristic length scale between each break-up lines. This length scale is directly related to the

tensile strength of the ice for a given wind forcing. The position of the flaw lead before and after these events, along with the characteristic scale of the resulting ice floes, are used together with the simulated internal ice stress field to infer the mechanical properties of sea ice. The results from a collection of events will then be used to investigated the relationship between the ice thickness and the ice strength, the timing of the land-fast ice stabilisation, the formation of ice bridges and the seasonal break up.

Bourdages, L., B. Tremblay, "Characterizing the biases in the simulated surface inversion over Arctic sea ice and their potential impacts on future sea ice decline", now an abstract to the CESM workshop; to be published in December 2015.

The Arctic atmosphere is characterized by a pervasive low-level temperature inversion, resulting from the balance of surface heat fluxes, as well as upper-level atmospheric heat fluxes from the mid-latitudes. With a diminishing sea ice cover, surface heat fluxes are modified, with expected implications for the temperature inversion and related climatic features such as Arctic haze mixing in the boundary layer, cloud formation and the lapse-rate feedback, among others. In this study, we use the Community Earth System Model (CESM) Large Ensemble (Kay et al. 2014) to study projected changes in temperature inversion in response to changes in sea ice cover. We find a strong seasonal signal, with significant decreases and increases in temperature inversion strength during the winter and summertime, respectively. Wintertime decreases are shown to be linked to a decrease in sea ice thickness, whereas summertime increases are related to atmospheric warming in regions of ongoing sea-ice melt.

Jutras, M., B. Tremblay, "Inertial oscillations in sea ice and the surface ocean: impact on vertical mixing in the ocean", now an abstract at the FAMOS workshop in WHOI, to be published in September 2016 (Masters Thesis).

Inertial oscillations are observed in sea ice drift particularly in the summer and fall when ice floe interactions (internal sea ice stresses) are weak. With the thinning of sea ice observed in the last decades, sea ice drift speeds, inertial oscillation amplitudes and seasonality have increased. Inertial oscillations in sea ice are coupled with inertial oscillations in the surface ocean. The latter excites internal wave, increased shear at the base of the mixed layer and enhanced mixing in the ocean. Monitoring inertial oscillations is therefore a good proxy for thinning of sea ice and increased mixing in the surface ocean in turns influences vertical ocean heat flux and the sea ice mass balance. We quantify these processes using buoy data from the International Arctic Buoy Program, the Ice Tethered Profiler buoy program, a coupled mixed-layer sea-ice model and a fully coupled ice-ocean GCM.

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Under internal review: to be submitted shortly.

1- Tremblay, B., A. Slavin, D. Straub, "Large vertical oceanic heat flux in the Arctic Ocean: a potential feedback for rapid sea ice decline, submitted to Nature, 2015.

2- Robert Newton, R., S. Pfirman, P. Schlosser, L.B Tremblay, M. Murray, M. Gerrard, ``White Arctic vs. Blue Arctic: A Case Study of Diverging Stakeholder Responses to Environmental Change", Earth's Future, 2015, to be submitted this month.

3- Slavin, A., L.B. Tremblay, D. Straub, "Vertical ocean heat fluxes beneath Linear Kinematic Features in the Arctic Ocean, Journal of Geophysical Research.

4- Renaud-Desjardins, L., L.B. Tremblay, "Abrupt reduction in summer Arctic sea ice and the partitioning of ocean heat flux between the Fram Strait and Barents Sea gate", now an abstract at the Ocean Science Meeting (2016), to be submitted to Journal of Geophysical Research Oceans.

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1- DeRepentigny, P., L.B. Tremblay, R. Newton, S. Pfirman, "Patterns of Sea-Ice Retreat in the Transition to a Seasonally Ice-Free Arctic, Journal of Climate, in revision.

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1- Williams, J., L.B. Tremblay, R. Newton, R. Allard, "Dynamic preconditioning of the September sea-ice extent minimum", Journal of Climate.

2- Blanken, H., L.B. Tremblay, S. Gaskin, A. Slavin, `` Arctic Oil Spills: A Risk Assessment of Transport in Sea Ice and Ocean Surface Waters from Ten Potential Spill Sites Marine Pollution Bulletin, Marine Pollution Bulletin, 2015.

3- Hata, Y., L.B. Tremblay, ``A 1.5D Anisotropic Sigma-Coordinate Thermal Stress Model of Sea Ice: validation against an Ice Stress Buoy deployed in the Canadian Arctic Archipelago", Journal of Geophysical Research.

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